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RIKEN heavy ion accelerator facility

M Kase

RIKEN, Wako-shi, Saitama 351-01, Japan

Abstract : Since July 1989, RIKEN Ring Cyclotron (RRC) has been coupled with the new injector K70 AVF Cyclotron as well as the former injector, heavy ion linac RILAC. The beam of 135 MeV/u $^{14}N^{7+}$ was successfully extracted from RRC using the new injector. This energy is the design goal in RRC for ions with mass of 4-20. Now beams with a remarkably wide range of mass and energy is available for experiments by choosing these two injectors.

Keywords : Heavy-ion accelerator, beam of 135 MeV/u $^{14}N^{+7}$, applications.

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1. Introduction

A new heavy-ion accelerator facility was fully completed in 1989 at RIKEN after a fifteen-year construction period. It houses a main accelerator of a K540 ring cyclotron (RIKEN Ring Cyclotron, RRC) and its injectors of a heavy-ion linac (RIKEN Heavy-Ion Linac, RILAC) and a K70 AVF cyclotron. This accelerator system provides various heavy-ion beams ranging from proton to bismuth with energies between a few tens of MeV/u and two hundred MeV/u at maximum. The facility is the first comprehensive research center for heavy-ion science in Japan.

The linac, which is of a frequency tunable type, was completed in 1981, and subsequently the construction of the ring cyclotron started. In December 1986, the ring cyclotron coupled with the linac was commissioned. The routine operation of ring cyclotron-linac complex began in April 1987, the year of which is the 50th anniversary of completion of the Japan–first cyclotron built at RIKEN by Professor Nishina, the pioneer of nuclear physics. Doing the experimentalists beam services by this complex, we constructed the new injector AVF cyclotron equipped with an ECR ion source, fabricated various experimental setups, and extended the beam distribution lines. This work was finished at the end of March 1989. In July we succeeded in extracting a 135 MeV/u $^{14}N^{7+}$ beam from the ring cyclotron in the AVF injection. This beam has the largest magnetic rigidity that the ring cyclotron can provide, and the highest energy obtained by cyclotrons in the past. Since last September, the experimental programs have been carried out by using both RILAC and AVF injected beams.

Up to the present, fifteen kinds of ion-species ranging from carbon through xenon with energies of 8.5-135 MeV/u were accelerated, and most of them were

The text and the references are printed according to the author's style used for experiments of nuclear physics, atomic physics, nuclear chemistry, material science and radiobiology. High quality beams with transverse emittances as small as 10 mm. mrad, an energy spread of approximately 0.1% and a pulse width shorter than 300 psec were extracted.

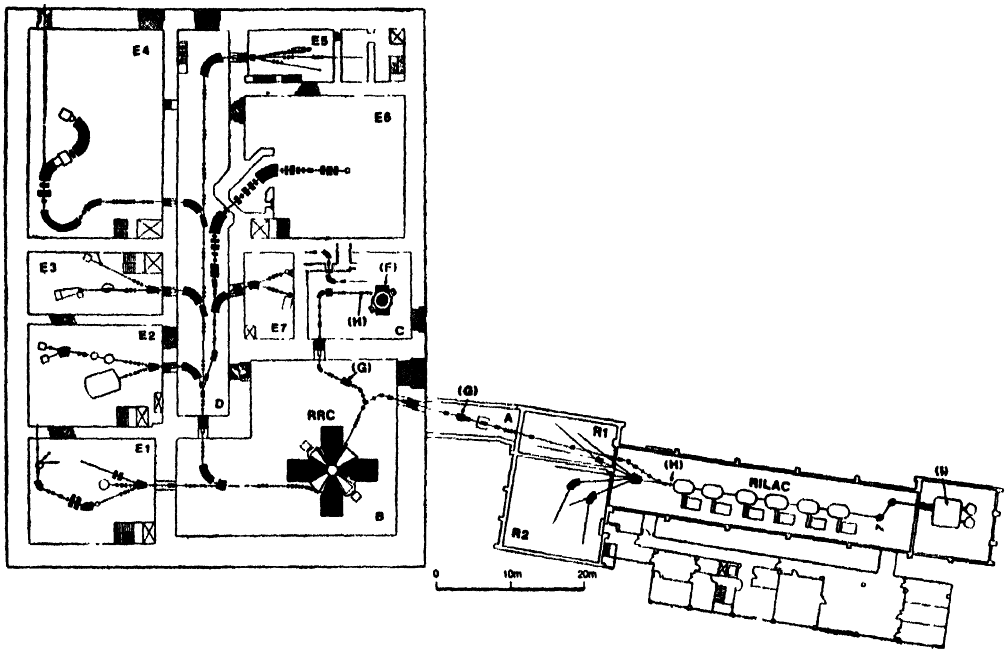

Figure 1. A layout of RIKEN Accelerator Research Facility.
A : connection building,
B : RIKEN Ring Cyclotron (RRC) vault,
C : injector AVF cyclotron vault,
D : beam transport system,
E : experimental rooms (see Table 3 in detail),
F : K70 AVF cyclotron with an ext. ECR ion source,
G : rebunchers,
H : charge strippers, and
I : 500 kV injector with a PIG source.

Figure 1 shows the general layout of RIKEN Accelerator Research Facility (RARF). The beams have been delivered to every experimental course except for the big spectrometer (under construction) in E4 room.

2. Operation status

2.1. Injector AVF cyclotron :

The K70 AVF cyclotron[1]) built as the second injector of RRC has four spiral sectors and two rf dees with an angle of 85 degrees. Its mean extraction radius of 71.4 cm is the four-fifth of the mean injection radius of RRC. The rf frequency is tunable from 12 MHz to 24 MHz, and the harmonic number of 2 is used for acceleration. The maximum average field is 17.5 kG. This cyclotron can accelerate particles having a m/q value smaller than 4 upto 3.8 MeV/u (at 12 MHz)-14.5 MeV/u (at 24 MHz), and serves as the injector of RRC for ions lighter than around copper. The assembled AVF cyclotron is shown in Figure 2.

Two types of external ion sources (the ECR ion source and a duoplasmatron) are placed on the floor above the cyclotron vault. The ECR ion source[2], which

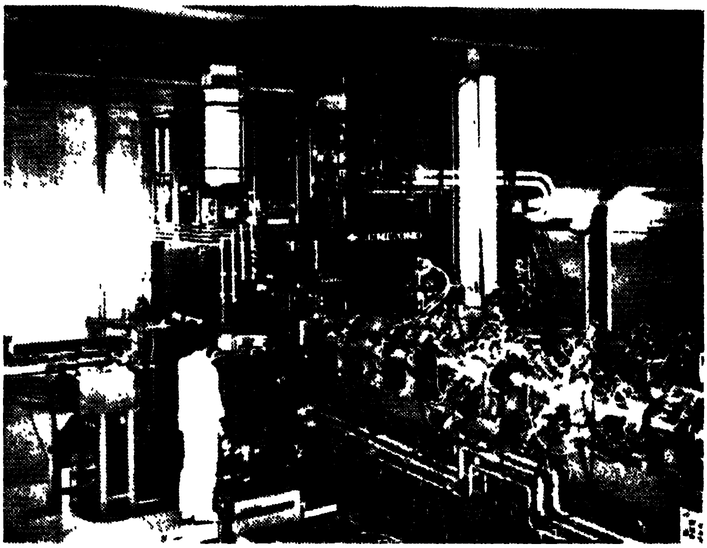

Figure 2. A photo of the injector AVF cyclotron as viewed from downstream of the extraction beam line.

was modified from the LBL's, has been in operation for three years, and achieved high performances. It is of a two-stage configuration, and 10 GHz microwaves are applied to both stages. The mirror ratio is variable between 1.4-1.8. Table 1 shows some of the operational results. For production of metalic ions (Al and Mg), a ceramic rod made of their oxides is inserted radially onto the second-stage ECR plasma boundary. The rod of 4 mm in diameter and 200 mm in length must be moved inside by about 0.1 mm every 15 minutes so as to compensate the evaporation of its end. This source has also been providing a highly-charged very low-energy beam to atomic physics experiments.

The beam from the source is injected axially into the AVF cyclotron through a spiral inflector. A beam buncher generating a sawtooth-like wave voltage in a single gap between a couple of meshes is placed 2 m upstream from the inflector. A compression factor of this beam buncher is estimated to be between 5-6.

This cyclotron was installed in the ring cyclotron building in December 1988. In April 1989 we injected a beam of $^{14}N^{5+}$ from the ECR ion source into the AVF cyclotron, and succeeded in accelerating it upto 7 MeV/u that is the maximum injection energy to RRC. The typical turn pattern inside the cyclotron measured

Table I. The result of operational test of RIKEN ECRIS.

Particle	Charge	Intensity (eμA)	AVF Energy (MeV/u)	RRC Energy (MeV/u)
^{12}C	4	56	7	135
^{14}N	5	110	7	135
^{16}O	5	120	7	135
^{19}F	7	18	6.1	115
^{20}Ne	7	50	7	135
^{24}Mg	7	12	5.5	100
^{27}Al	7	18	5.5	100
^{32}S	9	16	5.5	100
^{40}Ar	11	30	5.2	95

These data except for those of ^{24}Mg and ^{27}Al are referred to ref. 2.

by a radial differential probe is shown in Figure 3. So far, three kinds of ion species, ^{14}N, ^{18}O and ^{24}Mg were accelerated and injected to RRC.

The transmission efficiency between before injection and after extraction is improved significantly in use of the above beam buncher ; it amounts up to 20-30%.

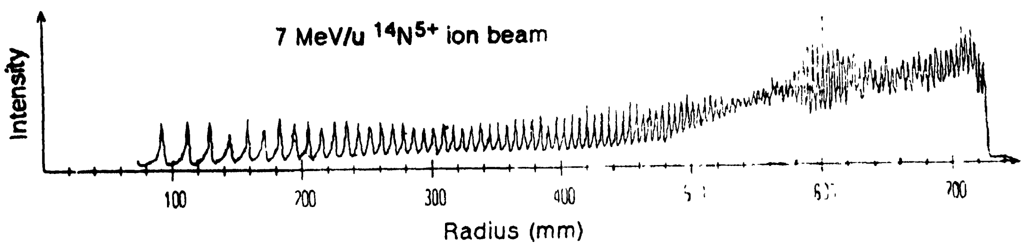

Figure 3. Turn patterns inside the AVF cyclotron measured with a radial differential probe for a 7 MeV/u $^{14}N^{5+}$ beam.

The single turn extraction, which can be achieved by a careful tuning, is indispensable to obtain better transmission through the RRC.

2.2. Ring cyclotron, RRC :

The main accelerator, K540 ring cyclotron[8] is made up of four straight-edge separate sector magnets and two rf dees. Its plane view and picture are shown in Figures 4 and 5, respectively. The sector angle of the magnet is 50 degrees ; the maximum magnetic field 16.7 kG. Isochronous fields are created by main coils and 26 pairs of trim coils mounted on the pole surfaces. A couple of delta-shaped rf resonators are placed at the opposite side of each other in the magnet valleys. The frequency range of 20-45 MHz is tuned coarsely by moving the boxes inside the cavity, which is our original mechanism for changing the resonant rf frequency[4]. The rf power is fed to the cavity through a 50 ohm coaxial line by a final amplifier composed of a 300 kW max. tetrode (SIEMENS 2042SK). At

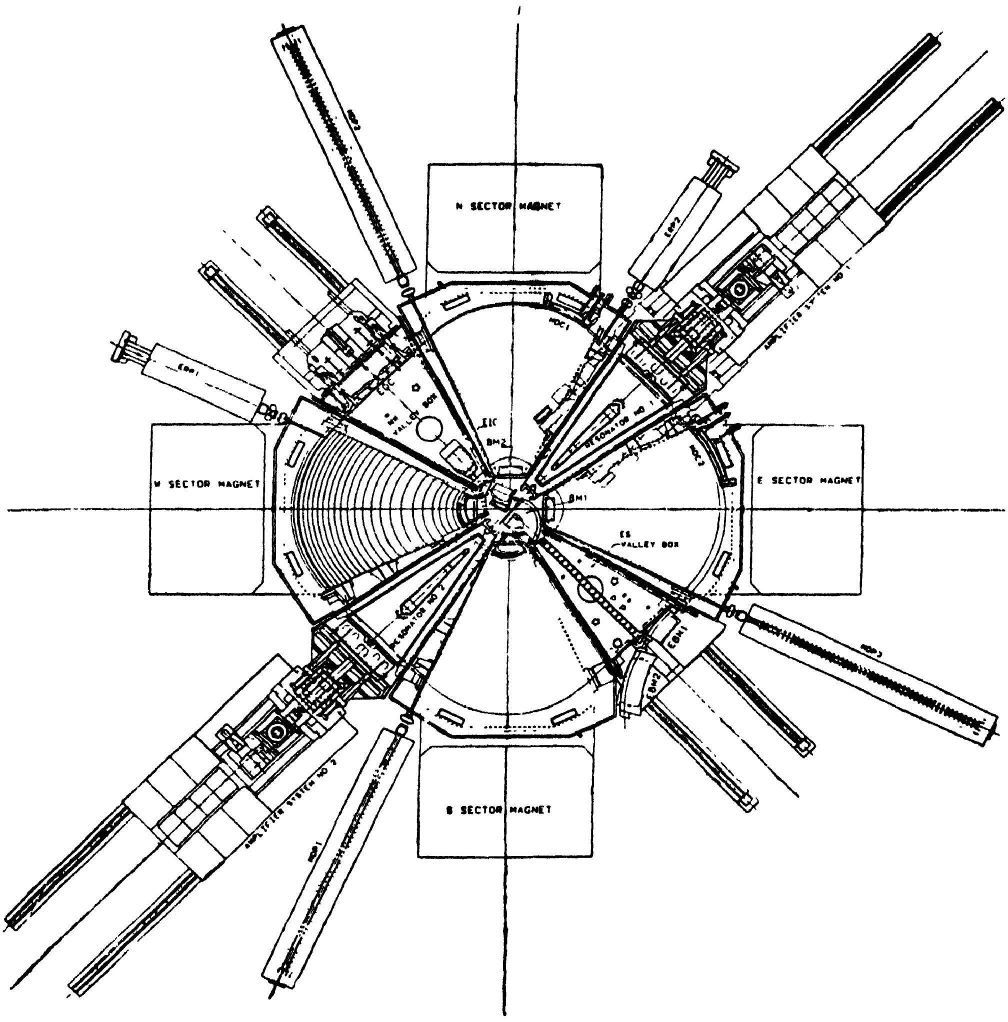

Figure 4. A plane view of RIKEN Ring Cyclotron (RRC).

present an rf voltage of 275 kV is generated by a 200 kW power between 10 cm dee gaps at 32.6 MHz, corresponding to the nitrogen top energy. The acceleration harmonic number of 5 is used for the AVF injection, while 9-11 for the RILAC injection. RILAC works at the same frequency as RRC, while AVF at half of RRC frequency. The large vacuum chamber of 30 m^3 in volume is evacuated by means of fourteen cryopumps of 1.2×10^4 l/sec in total speed to maintain the pressure as good as 10^{-8} Torr. The mean injection and extraction radii are 0.89 m and 3.56 m, respectively ; thus a final velocity becomes four times of an incident velocity.

within half an hour. Otherwise, it takes almost one day to change a beam energy.

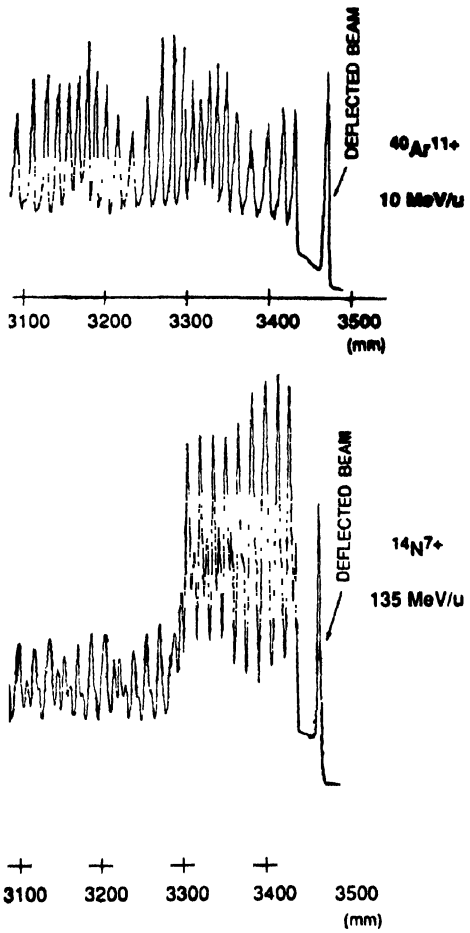

Figure 6. Turn patterns in the extraction region of RRC for a 10 MeV/u $^{40}Ar^{11+}$ beam (top), and for a 135 MeV/u $^{14}N^{7+}$ beam (bottom). The last peak is obtained after deflected by an electrostatic declection channel.

2.3. *Heavy-ion linac, RILAC :*

RILAC[5], a variable frequency heavy-ion linac, consists of an injector (DC max. 500 kV) and six acceleration tanks of the Wideroe type. The frequency tunability was required for a coupled operation with the post accelerator RRC. Its range covers 17-45 MHz, while the lowest frequency used in an injector mode to RRC is 20 MHz, corresponding to the RRC frequency range of 20-45 MHz. The maximum effective acceleration voltage is 16 MV. In this injector mode RILAC is able to accelerate particles having a m/q value smaller than 20 upto the energies of 0.8 MeV/u (at 20 MHz)-4.0 MeV/u (at 45 MHz). Figure 7 shows the chain of the acceleration tanks.

One of the advantages of this linac is that in fixing a frequency, the output beam energy can be decreased continuously from the nominal (sychronous) value by shifting an rf voltage and adjusting a phase of the last acceleration tank used, and by switching off some acceleration tanks when a large energy decrease is demanded. In use of this technique the output beam energy from RRC at a given rf frequency can also be decreased from the nominal value, but discretely in this

Figure 7. A photo of RILAC viewed from a side of a pre-injector.

case, by increasing an acceleration harmonics of RRC from the normal number of 9. In Table 2 the last tank of RILAC was switched off when the $h = 10$ mode operation was done in RRC.

The machine has worked well for nine years and been used for the low-energy experiments, mainly atomic physics and material science. While the RRC is combined with the AVF cyclotron, the RILAC beam service or its maintenance is done independently. The PIG ion source so far used will be replaced by the ECR ion source as mentioned later ; thereby the RILAC performance will be greatly improved.

2.4. Beam lines and experimental apparatus :

On the injection beam transfer lines of the injectors-RRC, charge strippers and rebunchers are placed. The charge strippers (an assembly of carbon foils with a thickness of 10-80 $\mu g/cm^2$) are located at the exits of the injectors, while the rebunchers are on half way of this beam transfer line. These rebunchers are operated in the second harmonic of the RRC rf frequency, and make the beam time-focused at the injection point of RRC.

The bending magnet immediately after RILAC works also in an AC mode, which generates a pulsed magnetic field having rise and fall times of 10 msec and a flattop duration variable from 10 msec to continuation. It provides a time-sharing of the beam between the RILAC experiment room and the RRC experiment room ; this is used for thinning out the beam as well.

On the beam distribution lines of RRC, the first bending magnet of the branch line to each experiment room except for E5 works also in an AC mode, and provides

Table 3. RRC Experimental apparatus.

E1 :	(Top)	Large Acceptance Beam Line
	(Mid.)	Radiation Shielding Exp. Setup
	(Bot.)	Gas-Filled Recoil Isotope Separator (GARIS) with Ion-Guided Isotope Separator On-Line (IGISOL)
E2 :	(Top)	Highly Stripped Ion Spectrometer
	(Bot.)	Large-Scale Scattering Chamber (ASCHRA)
E3 :	(Top)	Short-Lived Isotope Production System
	(Bot.)	BaF_2 Crystal Ball Spectrometer and Pion Spectrometer
E4 :		High-Resolution Charged-Particle Spectrometer and Neutron TOF Beam Line
E5 :	(Top)	Biological Irradiation System with Wobbler Magnets
	(Mid.)	Medical Science Irradiation Line
	(Bot.)	Spare
E6 :		Projectile Fragment Separator (RIPS) with Incident Angle Swinger
E7 :	(Top)	Slow Beam Channel (Material Science)
	(Bot.)	Large Ω Muon Channel

a time-sharing of the beam between two experiment rooms. The pulsed magnetic field has a stepwise time structure with rise and fall times of about 1 sec and a flattop duration variable from 1 sec to continuation.

In this facility seven experiment rooms E1-E7 (shown in Figure 1) are prepared for research fields of nuclear physics, atomic physics, nuclear chemistry, material science and radiobiology. The highly stripped ion spectrometer at E2 is used by the atomic physics group, and the isotope production system at E3 by the nuclear chemistry group. E5 and E7 are dedicated to radiobiology and material science, respectively. In the other rooms or beam lines, various kinds of experimental apparatus for nuclear physics are located. Only the big spectrometer at E4 is under construction, and will be completed in April 1990. The experimental apparatus in the facility is listed in Table 3.

3. Future program

When the AVF beams are injected to RRC, we will obtain protons of 210 MeV and ^{3}He particles of 185 MeV/u. The maximum energy of 135 MeV/u corresponding

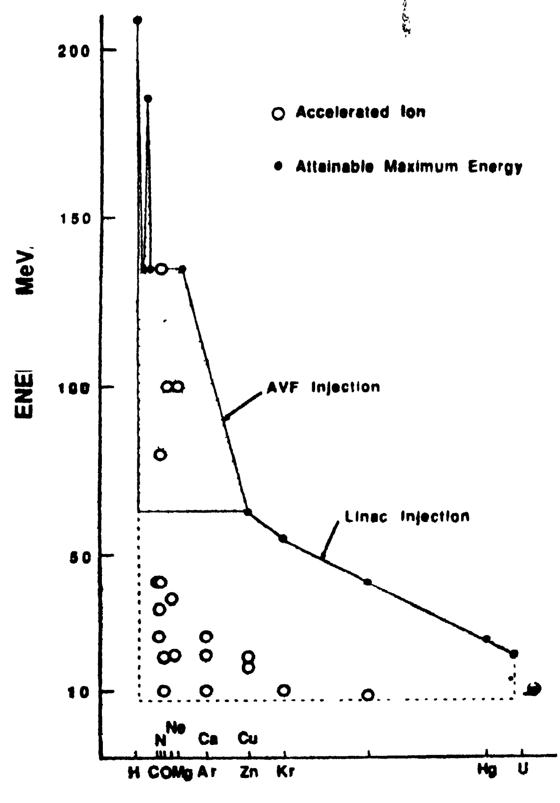

Figure 8. The relation between mass and energy of beams that RRC provides. Open circles indicates the beams so far accelerated by RRC. Solid lines with solid circles show the expected maximum energies. A shadow part corresponds to beams obtained in the AVF injection.

to the bending limit of RRC will be attained for light heavy ions upto Ne, and 95 MeV/u for Ar. Tests of some of these beams are scheduled to start in a few months.

For grading up the RILAC performance we put an order of a permanent-magnet ECR ion source, NEOMAFIOS, to CEA/IRF (Grenoble, France) as the new ion source of RILAC, and we have received it just now. It is an 8 GHz ECR ion source with a small size, consuming a low electric power smaller than 20 kW in total, which is suitable for installation inside a cage on a high voltage terminal. A preliminary test in Grenoble says that more than one μA currents are obtained for $^{84}Kr^{15+}$, $^{131}Xe^{20+}$, and $^{197}Au^{23+}$. A bench testing in our institute is being started in March. Through a few-month test, we will install this source on the 500 kV terminal, a pre-injector for RILAC, in place of the old PIG source. Using this new source we can push up the heavy-ion beam energies. The maximum energies for Kr, Xe and Au are expected to be 48, 42 and 30 MeV/u, respectively. The beam tests will be started in autumn of 1990.

Figure 8 shows the plots of the ions already accelerated on an enegy-mass space together with the feasible region of RRC. We are planning to introduce a polarized proton and deutron source, and a polarized ^3He ion source (being developed) to the AVF cyclotron within three years.

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